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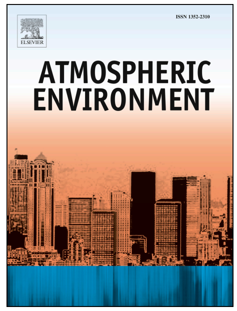

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REVIEW OF THE EFFICACY OF LOW EMISSION ZONES TO IMPROVE URBAN AIR QUALITY IN EUROPEAN CITIES

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ABSTRACT

Many cities still exceed the European Union (EU) air quality limit values for particulate matter (PM_{10}, particles with an aerodynamic diameter less than 10 µm) and/or nitrogen dioxide (NO_2). In an attempt to reduce emissions approximately 200 low emission zones (LEZs) have been established in 12 EU countries. These restrict the entry of vehicles based on the emission standard the vehicles were originally constructed to meet, but the restrictions vary considerably. This paper reviews the evidence on the efficacy of LEZs to improve urban air quality in five EU countries (Denmark, Germany, Netherlands, Italy and UK), and concludes that there have been mixed results. There is some evidence from ambient measurements that LEZs in Germany, which restrict passenger cars as well as heavy duty vehicles (HDVs), have reduced long term average PM_{10} and NO_2 concentrations by a few percent. Elsewhere, where restrictions are limited to HDVs, the picture is much less clear. This may be due to the large number of confounding factors. On the other hand there is some, albeit limited, evidence that LEZs may result in larger reductions in concentrations of carbonaceous particles, due to traffic making a larger contribution to ambient concentrations of these particles than to PM_{10} and $PM_{2.5}$. The effects of day to day variations in meteorology on concentrations often mask more subtle effects of a LEZ. In addition, separating the direct effects of a LEZ from the effects of other policy measures, the economy and the normal renewal of the vehicle fleet is not easy, and may give rise to false results.

Key Words: Low Emissions Zone; LEZs; NO_2; PM_{10}; vehicle emissions; air quality

1. INTRODUCTION

A large proportion of the European population continues to be exposed to poor air quality despite the significant reduction in emissions over the last few decades. The last evaluation by the European Environmental Agency (2014) has estimated that, during 2012, 21-33% of the urban population live in areas where the PM_{10} limit value is exceeded, and 64-83 and 91-93% where the WHO PM_{10} and $PM_{2.5}$ guidelines are exceeded. Whilst the adverse health effects of particulate matter (PM) are well documented (WHO, 2005, and WHO, 2013) there is increasing evidence of the health effects of long term exposure to NO_2 (WHO, 2013).

The European Union (EU) air quality Directive (2008/50/EC) requires the limit values for PM_{10} and NO_2 to be achieved by 2005 and 2010 respectively, but also allows the compliance to be delayed until 2010 and 2015 respectively subject to the Member State submitting an acceptable air quality action plan for non-compliant agglomerations and zones. Most EU member states have sought time extensions for one or both these pollutants.

In an effort to comply with the air quality limit values, and to protect human health, a number of European cities have introduced low emission zones (LEZs). In the nearly two decades since the first one was established LEZs have become regarded as an important measure to improve urban air quality, and there are thought to be approximately 200[1] currently in existence in Europe (Sadler Consultants Ltd, 2014a).

Whilst there are a large number of LEZs there have been few good quality studies quantifying their impact on air quality using monitored data. As the ultimate aim for many LEZs is to contribute towards compliance with the EU limit values, which are largely assessed thorough monitoring ambient concentrations, this is perhaps surprising. Many cities have assessed the cost-effectiveness of introducing a LEZ pre-implementation using emissions modelling and, in some cases, dispersion modelling to assess their potential impact, but there have been few post-implementation studies published.

[1] This assumes that the approximately 1550 mainly small LEZs in the Lombardi region of Italy count as one LEZ.

The aim of this review is to describe the types of LEZ in the EU and to assess the evidence of their efficacy, focusing largely, but not exclusively, on ambient air quality measurements. It reviews studies undertaken in five EU countries (Denmark, Germany, Netherlands, Italy and the UK), and is based on a literature search of peer reviewed papers using a range of relevant terms and databases. To identify reports commissioned by city and Government agencies a Google search was also undertaken. As the searches where undertaken mainly in the English language and it is probable that some relevant studies were missed. In addition not all relevant studies may be available on the internet.

It discusses the evidence from the London LEZ in more detail than other LEZs as it is probably the most extensively studied and certainly Europe's largest LEZ. Both modelled and measured data has been discussed, to provide an insight into the often optimistic results of modelling studies. For other LEZs the evidence is limited to ambient monitoring data.

A number of other urban scale traffic measures have been introduced into European cities, such as parking restrictions, road and bridge charges, and bus lanes that discriminate in favour of low emission vehicles. Another measure that is favoured in some European countries is the use of short term vehicle restrictions to reduce emissions during pollution events. These measures, whilst mentioned in passing, have not been included in the main part of this review, as these are not strictly LEZs, although there are similar or greater difficulties in assessing the success or otherwise of these measures.

2. LOW EMISSION ZONES

In broad terms LEZs are areas where access is restricted due to the emissions of certain road vehicles. The restriction is generally based on the emissions standard the vehicle was constructed to and may be a complete ban or there may be a charge to enter the LEZ. It may cover a few roads or a large inner city area.

European emission standards apply to passenger cars and vans (i.e. light duty vehicles; LDVs), two/three wheeled vehicles and the engines used in heavy duty vehicles (HDVs). Each type of vehicle has different emission limits and test procedures. For LDVs there are separate requirements for gasoline and diesel vehicles. For LDVs Arabic numbers (Euro 1, Euro 2, etc.) and HDVs Roman numbers (Euro I, Euro II, etc.) are used to identify the emission standards. This convention has been used in this paper.

A LEZ essentially introduces a step change in the normal fleet turnover, resulting in lower emissions than would have occurred without the LEZ. Over time the fleet emissions will become similar to those that would have occurred without the LEZ. For further benefits it is necessary to periodically tighten the scheme's criteria.

The LEZs are mainly aimed at reducing exhaust emissions of PM, although some also aim to reduce nitrogen oxides (NO_x). These emissions are greater from diesel vehicles than from conventional gasoline vehicles (assuming, for NO_x, a three-way catalyst is fitted). HDVs, which are almost all diesel fuelled in Europe, have the greatest emissions per vehicle kilometre. For example, Wang et al. (2010) suggests that in an urban area in Copenhagen HDVs emit about 30 times more $PM_{2.5}$ and 26 times more NO_x than LDVs. Therefore many LEZs restrict these vehicles.

2.1. Brief History of LEZs

The first LEZs in Europe were established in 1996 in Stockholm, Göteborg and Malmo in Sweden, where they are known as Environmental Zones (Miljözon). The oldest HDVs were banned, and middle aged HDVs had to be fitted with a certified emission control device or new engine (Göteborgs Stad, 2006). In 2002 the entry criteria were modified to include restrictions on NO_x emissions. In 2006 the Swedish Government established a national LEZ scheme. The current requirements are that Euro II and III HDVs can be driven in a LEZ for eight years from first registration, Euro IV until 2016 and Euro V until 2020 (Göteborgs Stad et al., 2009).

The first LEZ outside Sweden, established in 2002, was in the Mont Blanc Tunnel between France and Italy. HDVs are banned from entering unless they meet at least the Euro III standard.

2.2. Summary of European LEZs Requirements

Table 1 summarises the LEZ requirements. Only HDVs are restricted in most countries, but in Germany LDVS are included as are cars in Athens (Greece) and Lisbon (Portugal). The Italian LEZs also restrict 2-wheeled vehicles

There are a large number of LEZs in Italy and Germany, but other countries have been less enthusiastic. In France, according to Charleux (2013), legislation was passed in 2010 to allow large urban communities to introduce LEZs, but following a change in government, the policy was abandoned. However, the Mayor of Paris (2015) has announced the establishment of a LEZ in the capital from the summer 2015.

According to Sadler Consultants Ltd. (2014a) most LEZs are permanent and apply 24 hours a day, seven days a week. Some, however, only apply on weekdays (Athens and Budapest LEZs) and the Lisbon LEZ only applies for 12 daytime hours on Monday to Saturday. Some Italian LEZs only restrict passenger cars in the winter, but restrict 2-stroke motorcycles and mopeds, and diesel public transport buses all year. Athens LEZ applies from September to July each year, with different requirements within the city centre and the rest of Athens. Vehicles up to 2.2 t are allowed to enter the city centre on alternative days depending on the last digit of the license plate. In the whole of Athens vehicles over 2.2 t and first registered before 1 January 1991 are banned. The date increases by one year, every year. LEZ restrictions are enforced by manual techniques or the use of automatic number plate recognition technology. Most LEZs require a sticker indicating compliance to be displayed.

2.3. National Frameworks

Some countries, (e.g. Germany, the Netherlands and Sweden) have national LEZ frameworks to provide a consistent approach and to increase the ease of driving across a country. However, each municipality has the option to declare a LEZ and to determine the exempt vehicles. In other countries, most notably Italy, there is no national framework and each municipality determines their own criteria. This approach has the potential advantage of tailoring the LEZ to the local air quality issues, but can make driving thorough several cities on a single journey problematic without researching the requirements prior to starting the trip. It can also increase costs for national transport companies, as the most stringent requirement(s) would need to be met to provide a national service.

2.4 Evaluating the Effectiveness of an LEZ

During the planning stage potential impacts can be quantified by emissions modelling, often combined with an estimate of the impact on air quality using dispersion or empirical models. There have been relatively few studies which have attempted to evaluate the impact of a LEZ using measured concentrations, possibly because of the difficulty in identifying small changes in concentrations following policy interventions.

To predict the potential LEZ impact a large amount of detailed local data is required, from the fleet structure to traffic speeds. In recent years there has been considerable uncertainty regarding the emission factors commonly used, such as those in the EU's COPERT 4 emission model (EMISIA, 2011), particularly for nitrogen oxides (NO_x). As a consequence many of the emission inventories and forecasts have been shown to be optimistic (Beevers et al., 2012).

Carslaw and Rhys-Tyler (2013) show that under real world driving conditions diesel car NO_x emissions have not changed over the last 20 years, and that this has not been reflected in the emission factors. At the same time the proportion of NO_2 in vehicle NO_x emissions has increased. For heavy goods vehicles (HGVs) NO_x emissions were fairly constant until Euro IV when they declined by about 30% while there has been little change in urban buses emissions from Euro 1 to Euro IV, and there is some evidence that some Euro VI buses continue to be high emitters.

Given the relatively high NO_x emissions from diesel vehicles and the lack of improvement over time, any LEZ targeting NO_2 concentrations is unlikely to be successful until NO_x emissions are significantly reduced under real world driving conditions.

Another factor that needs to be considered when assessing the impact of a LEZ is the contribution of exhaust emissions from local traffic to ambient concentrations. In Berlin, for example, Lutz (2013) estimated that just 4.1% of PM_{10} at kerbside sites in 2009 was due to traffic exhaust emissions, with a larger contribution (14.9%) from non-exhaust traffic emissions. However, the regional background dominated, contributing almost two thirds of the PM_{10}. In situations such as this, reducing local vehicle exhaust emissions can only have a very limited impact on PM_{10} concentrations and compliance with the EU limit values.

It has been argued, for example by Cyrys et al. (2014), that it may be more appropriate to assess the impact of LEZs in terms of the reduction in elemental carbon (EC), black carbon (BC) or black smoke (BS) rather than PM_{10}, $PM_{2.5}$ or even PM_1. The former are considered by some to be more toxic than some of the other components of ambient PM and hence a reduction in their ambient concentrations may have a greater benefit for human health than a small change in PM_{10} concentrations may suggest. Janssen et al. (2011) evaluated the risk of BC and concluded that they are a valuable indicator of the health risks of poor air quality where there are significant combustion particles, and should be an additional indicator to PM_{10} and $PM_{2.5}$ due to other components also having health effects. Black smoke (BS), BC, absorption coefficient (Abs.), and EC are different instrumentally driven parameters reflecting the concentration of the graphitic component of the soot particles arising from fuel combustion. The traffic contribution to urban concentrations of these indicators is generally high, making it easier to detect the impact of policy interventions (Keuken et al., 2012).

Cyrys et al. (2014) noted that it is difficult to show a reduction in PM_{10} annual mean concentrations around 1 µg m^{-3} as meteorology has a large impact on the year to year variation of PM mass concentrations. Some studies have compared monitoring data from several months before and after establishing a LEZ. Adequate adjustment for the meteorological conditions can only be made over long periods, preferably one year or more, to remove seasonal biases, and even with annual mean data there can be significant year-to-year differences due to meteorology. This also means that assessing the contribution of LEZs to compliance of short term air quality standards is even more challenging.

2.5 Effects of other Policy Measures

Assessments of the impact of LEZs also need to take account of other policy measures implemented at a similar time. For example, the EU requirement for zero (<10ppm by mass) sulphur diesel (Jones et al., 2012), the effect of the implementation of the Euro standards and the German scrappage scheme for vehicles more than nine years old (Cyrys et al., 2014). In some locations there may also be a large change in traffic due to planned transport management schemes. The deep recession in Europe from 2008 is also likely to have affected the rate of replacement of vehicles and traffic volumes.

The difficulty in showing improvements to air quality as a result of traffic management interventions is illustrated by the London congestion charging scheme (CCS). It was introduced in 2003 and resulted in a 15% reduction in traffic within the zone (Transport for London, 2007). However, in 2003 air pollution concentrations were higher than in 2002 because of unusual meteorological conditions. Emissions modelling suggested total NO_x emissions in the charging zone reduced by 12.0% and on the inner ring road increased by 1.5%, and PM_{10} emissions reduced by 11.9% in the charging zone and 1.4% on the inner ring road (Beevers and Carslaw, 2005). However, when Atkinson et al. (2009) analysed measured concentrations from a roadside monitor in the CCS zone, they could not identify any changes in concentrations associated with the scheme. Kelly et al. (2011) undertook further analysis of monitoring data and showed small decreases in PM_{10} and larger decreases in NO_x, and small increases in NO_2 concentrations at background sites within the zone. However, attributing the cause of these changes to the CCS alone was not possible. The authors suggested that the rise in NO_2 could plausibly be explained by the bus fleet having been fitted with regenerative diesel particle filters as well as the increase in diesel vehicles, and the decrease in background NO could have been due to an increase in ozone concentrations.

3. LONDON LEZ

The London LEZ commenced operation in 2008 and is the world's largest. It covers an area of more than 1,500 km^2. It operates 24 hours a day, seven days a week, and uses cameras with automatic number plate recognition technology linked to vehicle registration data to monitor compliance. Foreign vehicle operators need to register prior to entering the LEZ. It has been introduced in a series of phases as shown in Table 2.

The operators of vehicles not meeting the emission criteria, or not registered, are charged a daily rate.

Barrett (2014) used automatic number plate recognition data to show that the compliance rate of HGVs greater than 12 tonnes at the North Circular air quality monitoring site changed from less than 80% in the 12 months prior to implementation to 95% by the implementation date, and then stabilised at about 98%. Transport for London (2008) found that 90% of the vehicle kilometres in Greater London were driven in compliant vehicles at the start of Phase 1. Ellison et al. (2013) suggests that the fleet turnover initially increased substantially but subsequently returned to the national average. Although the LEZ also applied to buses the vast majority were already Euro III compliant at the start of the study.

Transport for London (2014) found that compliance was 98.99% for Phase 3 and 95.81% for Phase 4 in the last quarter of 2013.

3.1. Modelling Studies

Transport Research Laboratory (TRL, 2000) concluded that a LEZ covering all of Greater London would be more effective than one based on a smaller area for reducing NO_2 concentrations because traffic emissions over a large area influence background concentrations in central London. For PM_{10} concentrations the size of the LEZ would make little difference because traffic contributes only about a third of the background PM_{10} concentration in central London. Therefore the scope to influence concentrations is less than for NO_2. Although the whole of London would benefit, emissions would reduce more in central London than in outer London, corresponding to the severity of the air quality. The most effective LEZ would exclude all pre-Euro 3 / III vehicles, but this was considered to be too challenging as restrictions on cars would affect too many motorists, would require major expenditure both to establish and enforce the LEZ, and would be disproportionate to the benefits. Therefore the study recommended that the LEZ should be restricted to taxis and medium and heavy duty vehicles.

Table 3 summarises the original estimates of the impact of the LEZ on annual average concentrations.

Watkiss et al. (2003) identified that it would be most cost-effective to target HDVs across the whole of Greater London. For these vehicles, due to their initial high costs, retrofitting is more cost effective than replacement. This is often not the case for LDVs. It was also recommended that the emission criteria should be progressively tightened in future years.

Table 4 shows the predicted reductions in emissions and the area of exceedence of the UK air quality objectives. The emission benefits are significantly less than those predicted for 2005. To some extent this is due to the emissions being estimated for 2007 and 2010, when the normal fleet turnover would have resulted in lower emissions, and therefore the benefits are predicted to be less, but is also due to a revision in the emission factors used. Watkiss et al. (2003) concluded that the proposed LEZ would have relatively little impact on NO_x emissions, but would be more effective at reducing the area of exceedance of the NO_2 objective. For PM_{10} the annual mean objective / EU limit values were expected to be achieved at all locations in 2007 with the LEZ even at the busiest roads in London.

Carslaw and Beevers (2002) modelled the effects of a central London LEZ at five locations in 2005. No adjustment was made for traffic growth. Restricting all HDVs to Euro III and banning all pre-Euro 1 light duty vehicles was predicted to reduce annual mean NO_2 concentrations by 3.6 to 11.1% or by up to 3.9 ppb (7.3 µg m^{-3}) at building façades close to busy roads. The introduction of the LEZ would not result in the annual mean concentrations being below the UK annual objective of 40 µg m^{-3} (21ppb).

3.2 Monitoring Studies

Jones at al. (2012) identified a large reduction in particle numbers from late 2007 when the HGV fleet was beginning to change in preparation for the implementation of LEZ in early 2008. The authors concluded, however, that it was more likely to be due to the introduction of zero sulphur diesel (less than 10 ppm by mass) which occurred over a similar time period than the introduction of the LEZ. However the authors did not preclude a small effect due to the introduction of the LEZ.

Ellison et al. (2013) compared roadside PM_{10} concentrations within the LEZ (in Enfield, Hackney, and Sutton) and outside the LEZ (in Sawbridge, north of London). They concluded that the Phase 1 LEZ may have reduced PM_{10} emissions by 2.47 to 3.07% within the zone compared to just 1% outside. No discernible differences were found in NO_x concentrations.

Barratt (2014) also compared roadside air quality data before and after the implementation of Phase 1. To isolate the impact of the LEZ on air quality from confounding factors a series of filters were used to remove the influence of non-local traffic pollution sources. In addition, the weekends were excluded from the dataset, as the proportion of HGVs was lower, to make any impact easier to detect. None of the sites showed any clear trend in the local traffic contribution (i.e. the filtered data) to ambient PM_{10} and NO_2 concentrations. At two outer London sites where HGVs dominate the traffic emissions the local traffic contribution of $PM_{2.5}$, black carbon and NO_x reduced with the LEZ, but not at the central London sites. The reduction in $PM_{2.5}$ concentrations with no observed reduction in PM_{10} concentrations suggests that coarse PM concentrations increased over the same period. This is may be due to the effect of increasing vehicle weight on non-exhaust emissions. The London LEZ was specifically introduced to help achieve compliance with the EU limit values for PM_{10}, and it was hoped that it would also have a beneficial impact on NO_2 concentrations. This study found no clear evidence of a reduction in either pollutant that could be attributed to the LEZ. However the reduction in $PM_{2.5}$ and particularly black carbon concentrations in outer London suggest that there may have been health benefits.

In summary, the modelling studies undertaken during the decision making phase suggest much larger benefits than have been observed. This is likely to be due to a number of factors including optimist assumptions regarding the NO_x emissions from diesel vehicles, their higher proportion of direct NO_2 emissions and the increase in the proportion of diesel LDVs. In addition, the large contribution from outside London to measured concentrations, particularly for PM_{10}, means that there is a limit to the emission reduction potential of any traffic related measure.

Because of the limitations of using modelled data, particularly the failure of the emissions modelling to reflect real world emissions, the rest of this paper has focused upon evidence of an impact from ambient air quality monitoring data.

4. GERMAN LEZs

Germany has a national LEZ framework which came into force in March 2007. To enter a LEZ (Umweltzone) a vehicle must have an appropriate sticker displayed on the windscreen or face a fine. There is manual enforcement of the LEZ by the police. There are three emission stickers: green, red and yellow. The green sticker indicates the vehicle is either diesel fuelled and meets at least Euro 4 or IV standards, is Euro 3 or III with a diesel particle filter (DPF), or is a gasoline vehicle meeting Euro 1 standards. All diesel vehicles constructed prior to 2000 are banned. A yellow sticker is for diesel vehicles meeting at least Euro 3 or III, or Euro 2 or II with a DPF, and built in 1996 or later, and a red one is for diesel vehicles meeting at least Euro 2 or II or Euro 1 plus DPF and built in 1992 or later. Vehicles not meeting any of these requirements are in pollution class 1.

Cyrys et al. (2014) noted that in 2009 and 2010 the German Government provided a subsidy of €2,500 to car owners replacing cars older than 9 years with a new model. The scrappage scheme led a more rapid update of the car fleet across Germany than would otherwise have occurred, and this may have interfered with LEZ impact studies.

According to Morfeld et al. (2014) German cities started requiring the green sticker from 2011; and Cyrys et al. (2014) states that most cities now require it. Two-wheeled vehicles, vintage cars, and off-road, police, fire brigade and emergency vehicles are exempt from the scheme.

Cyrys et al. (2014) reviewed German studies on the impact of LEZs on PM_{10} and diesel soot concentrations. Three studies showed no effect on monitored annual average PM_{10} concentrations, although one did show a reduction during the summer months. Other studies reported a reduction in PM_{10} concentrations in the range 5 to 15%, but these studies generally were undertaken over short periods or used simple statistical approaches. Studies of annual mean BS or EC concentrations tended to show a larger effect, up to 16%, reduction. This is thought to be due to vehicle exhaust emissions contributing a larger proportion to the total ambient concentration, and therefore there is greater potential for traffic measures to reduce concentrations.

Morfeld et al. (2014) investigated the effect of German LEZs on NO_x and NO_2 concentrations using matched quadruplets i.e. two pairs of 15 minute average concentrations from a street and reference station, before and after the introduction of 17 LEZs in Germany. They also used monthly passive diffusion tube data. The study showed a statistically significant but small impact of LEZs on NO_2 concentrations of less than 2 µg m^{-3}.

4.1. Berlin

The first German LEZ was established in Berlin. It is covers 88 km^2 of the central area of the city and approximately 10% of the total area of Berlin. About 1 million people live within the LEZ. Stage 1 (red, yellow or green sticker required) was introduced in January 2008 and Stage 2 (green sticker required). two years later on 1 January 2010.

According to Lutz (2009) during the planning phase it was anticipated that Stage 1 would result in a 3% decrease in annual mean PM_{10} concentrations and five fewer days with concentrations greater than 50 µg m^{-3}, and Stage 2 would reduce PM_{10} concentrations by 5 to 10% and NO_2 concentrations by about 4%. There would also be 10 to 15 fewer days with PM_{10} concentrations above 50 µg m^{-3} and approximately 10,000 fewer residents living along main roads in the LEZ in non-compliance with the PM_{10} standards. However, attempts to identify the direct effects of the LEZ on ambient PM_{10} concentrations failed as there was too much variation due to the weather and other unknown factors. In the first year of operation of the LEZ (red, yellow or green sticker) the EC concentrations, after accounting for the lower traffic volumes, decreased by 14 to 16% and NO_2 concentrations decreased by 8%.

4.2. Munch

The City of Munich established a LEZ (red, yellow and green sticker) covering 44 km^2, 14% of the city area, in 2008, eight months after a ban on HDVs driving through the city. Almost one third of the city population live within the LEZ.   In 2010 Stage 2 (yellow and green sticker) was implemented, and in 2012 the final stage (green sticker) was implemented.

Cyrys et al. (2009) (cited in Cyrys et al., 2014) compared PM_{10} concentrations measured in the LEZ with those at a regional background site close to the city. PM_{10} concentrations in the LEZ reduced by 5 to 12% at almost all the monitoring sites. However, Morfeld et al. (2013) (in German, cited in Cyrys et al., 2014) analysed the same data set using regression analyses of matched pairs of concentration data and found no significant effect.

Fensterer et al. (2014) used a sophisticated semi-parametric regression model over four years and showed statistically significant reductions in PM_{10} concentrations at a traffic monitoring site (13% average reduction, p-value <0.001) as a result of the Stage 1 (red, yellow and green sticker) LEZ. The PM_{10} concentrations were adjusted using concentrations at a reference station, wind direction, season, time of day, and public holidays. When the same statistical analysis was applied to the shorter period of data used by the earlier work of Cyrys et al. (2009), the authors found only negligible and statistically insignificant changes in PM_{10} concentrations. This study and Morfield et al (2013) illustrates the influence of the monitoring period and the statistical methods used on the results.

Qadir et al. (2013) analysed $PM_{2.5}$ samples collected before and after the implementation of the stage 1 (red, yellow and green sticker) LEZ. The contribution of traffic particulate organic compounds was found to decrease by about 60% with the LEZ and the average concentration of EC from traffic also decreased by a similar proportion.

5. ITALIAN LEZs

Italy has a very large number of LEZs (Zona a Traffico Limitato), mainly in the north of the country. There is no national scheme, and many Italian LEZs have complex requirements. Many are operational only during the winter and some only in the rush hour. There are regional LEZs which may have different entry criteria to the local LEZs within them. There are also extensive exemptions and the restrictions often apply only to very old vehicles. A vehicle's emission category is not indicated by use of a windscreen sticker as in many other countries, and according to Sadler, (2010) little is known regarding enforcement. There is little published data on their efficacy in the English language, except for the Milan LEZ, which is described below**.**

5.1 Milan

In 2008 the Municipality of Milan restricted certain vehicles entering an 8.2 km^2 area in the historic city centre, known as the Ecopass zone. Drivers of pre-Euro 4 / IV diesel vehicles had to pay a charge to enter the zone between 08:00 and 20:00. At the end of 2011 the scheme was replaced by a combined LEZ and urban road charging scheme known as Area C. There is also a LEZ covering the whole of the Lombardi region and another covering the Greater Milan area. The Lombardi LEZ is a permanent restriction on pre Euro 1 2-stroke motorcycles and mopeds and pre- Euro III diesel fuelled public buses. In addition, from October to April the Greater Milan LEZ restricts pre Euro 1 gasoline, and pre Euro 3 / III diesel vehicles from 7:30 to 19:30 on weekdays. Diesel vehicles fitted with a DPF to meet Euro 3 / III standards are allowed in the LEZ.

According to Invernizzi et al. (2011) the Ecopass zone was originally predicted by the municipality to reduce PM_{10} concentrations by 30%, but a study undertaken in 2009 failed to demonstrate any difference in PM_{10}, $PM_{2.5}$ or PM_1 concentrations inside and outside of the Ecopass area, despite a reduction in the number of vehicles entering the zone. The failure to find air quality improvements may be due to the small area of the Ecopass zone or due to that fact that PM_{10} concentrations are relatively homogeneous across Milan, due to the large regional component. The authors suggested that black carbon, from combustion of carbonaceous fuels, may be a more suitable indicator of the beneficial impact of LEZs and undertook a short term study of BC, PM_{10}, $PM_{2.5}$ and PM_1 concentrations in a pedestrian zone, the Ecopass zone and outside the Ecopass zone. The three day mean concentrations of PM_{10}, $PM_{2.5}$, and PM_1 were not significantly different at the three locations. However, the ratio of black carbon to PM_{10} in the three locations showed a decrease from outside the Ecopass zone > Ecopass Zone > pedestrian zone. The mean ratios were 22.6%, 11.8% and 8.5% respectively. On average the BC concentration was 47% and 62% in the Ecopass Zone and the pedestrian zone respectively of that measured outside the Ecopass zone.

6. DUTCH LEZs

According to Sadler Consultants Ltd (2014a) the Netherlands has a national LEZ framework which originally covered HGVs but was extended from 2011 to include LDVs. Entry was first restricted for pre-Euro III HDVs, and then, from 2013, tightened to pre-Euro IV vehicles. LDVs should be first registered after 1 January 2001. The national agreement defines a number of exempt vehicles, and allows for additional local exemptions. Up to 12 entries into the LEZ per year are permitted for non-compliant vehicles. Six Dutch LEZs (*Milieuzone*) were established in 2007and by April 2014 there were 13 LEZs.

Boogaard et al. (2012), in a study in five Dutch cities (Amsterdam, The Hague, Den Bosch, Tilburg and Utrecht), concluded that the LEZs did not substantially change concentrations of traffic-related pollutants at street monitoring sites more than at suburban background sites outside the LEZs, even though concentrations were lower in 2010 (post-implementation year) than in 2008 (pre-implementation year).

6.1 Amsterdam

Amsterdam introduced a LEZ in October 2008 covering an area of approximately 20 km^2. Initially it was a trial with no penalties or enforcement, but from January 2009 pre Euro III HDVs were prohibited from entering the LEZ. From 1 January 2010 the criteria was tightened to also prohibit Euro III vehicles without a DPF. Automatic number plate recognition is used to identify vehicles and penalties are issued automatically. The restrictions apply all the time and there is a fine for non-compliance (Milieuzones, 2014).

Panteliadis et al. (2014) found a statistically significant decrease in concentrations of NO_2, NO_x, PM_{10}, EC and Abs. measured at a roadside location in the Amsterdam LEZ. However data for EC and Abs. were not collected every day. When the limited data was compared to the full NO_2, NO_x and PM_{10} dataset, there was no noticeable difference in concentrations in the post LEZ implementation period. The authors suggested that the limited dataset may have biased the result, and over-estimated the impact on the LEZ by chance due to the selection of the sampling days for EC and Abs.

7. DANISH LEZs

Denmark also has national legislation defining LEZs. From 2008 HDVs in a LEZ had to meet the Euro II emission standards and from July 2010 the Euro III standards.

Jensen et al. (2011) investigated the effects of the Copenhagen LEZ using long term monitoring data from H.C. Andersens Boulevard, one of the busiest streets in the city. The authors concluded that the LEZ reduced average $PM_{2.5}$ concentrations by about 5%, equivalent to 0.7 µg m^{-3}. This was 12% of the traffic contribution. However, the authors noted the difficulty of identifying small changes in concentrations when there is a continuous renewal of the car fleet and associated reduction in emissions.

8. DISCUSSION

Approximately 200 LEZs have been declared in the EU, but there have been relatively few peer reviewed studies reported in the scientific literature demonstrating their impact using monitoring data. Table S1 in the supplementary information summarises the results of the available studies including those undertaken by municipalities. Modelling data has not been considered due to the uncertainty over the emission factors used, particularly for NO_x.

LEZs can only impact on the traffic component, which for PM_{10} and $PM_{2.5}$ is relatively small as the regional background often dominates. Also they do not impact on non-exhaust PM emissions from traffic which may be an equally or more important emission source, but is currently uncontrolled (Harrison et al., 2012).

Determining the impact on air quality is difficult due to a range of confounding factors, particularly meteorological influences, but also the traffic contribution, the changing nature of vehicle fleets, policies such as the introduction of vehicle scrappage schemes, the composition of traffic close to the monitoring stations and changes in vehicle flows. Economic factors such as recession and oil prices can also play an important role in determining the rate of new car purchase and use of vehicles.

The statistical method and period of data used to isolate the LEZ effect are also important. Some studies have used very simple statistics while other used detailed pairing or filtering of the data to identify an impact. Where comparisons are made between sites within and outside a LEZ over time it is important that traffic flow data is available as any improvement in air quality may be due to changes in traffic flows rather than the influence of the LEZ.

The data presents a mixed picture. This is not surprising as LEZs differ hugely in terms of the area covered and the vehicles restricted. Many of the studies of the efficacy of LEZs have been undertaken on early phases due to the need for long term monitoring data, and it may be that later phases are more effective.

Reductions in annual mean PM_{10} concentrations up to 7% have been reported in German LEZs, but in many LEZs no effect has been observed. In Munich the combination of a LEZ and a ban on HGVs travelling through the city centre has been shown to reduce PM_{10} concentrations by up to 13%. There seems to be a greater effect in the summer months, presumably because the traffic contribution is relatively large compared to the winter when other sources become more important. The German LEZs restrict diesel cars as well as pre-Euro 1 gasoline cars, and therefore a greater impact may be expected in these LEZ than in other countries where the LEZs typically only restrict heavy duty vehicles.

The impact of LEZs on the following PM metrics has also been evaluated: $PM_{2.5}$, PM_1,and carbonaceous particles. LEZs have been found to reduce $PM_{2.5}$ concentrations in London and Copenhagen, but not in Dutch cities or Milan. The only study investigating the impact on PM_1 concentrations found no effect, but it was a very short term study. A larger impact has generally been found on carbonaceous particles (BC, EC and Abs.). The traffic contribution to BC concentrations has been reduced by 15 to 17% in London, while the total EC concentration has been reduced by 13-16% in Amsterdam, Berlin and Leipzig, with the traffic contribution reduced by 56% in Berlin. However, there may have been a bias in the Amsterdam study, acknowledged by the authors, due to the sampling days. In addition, the results of the short term study in Milan suggested that the LEZ had a beneficial impact on BC concentrations. On the other hand, no impact on Abs. was found in several Dutch cities.

No impact of LEZs on NO_2 concentrations has been found, except in a multi-city study in Germany. Given the evidence that has emerged in recent years that real world diesel NO_x emissions have remained essentially unchanged per vehicle kilometre since the introduction of the Euro emission standards, with the probable exception of late Euro V and Euro VI HDVs, it is perhaps surprising that any benefit of LEZs on NO_x or NO_2 concentrations have been observed. It may be that other factors have contributed to the observed changes in NO_2 concentrations.

None of the studies reviewed have explicitly stated whether LEZs have contributed to compliance with the EU limit value for either PM_{10} or NO_2. Given the many confounding factors identifying the contribution would be challenging.

9. CONCLUSIONS

The original aim of many LEZs was to reduce ambient concentrations of $PM_{10,}$ and to a lesser extent NO_2, to help achieve compliance with the EU limit values. In German cities reductions in annual mean PM_{10} and NO_2 concentrations up to 7% and 4% respectively due to the implementation of an LEZ have been reported.

These LEZs may have helped achieve compliance with the annual mean limits but no data is available from air quality monitoring studies on whether LEZs have contributed towards the achievement of the short term limit values. To demonstrate compliance with these limit values would be challenging due to the large influence of meteorological conditions on the daily and hourly concentrations.

In other countries the picture is much more mixed with no effects generally being observed. This may be explained by the German LEZs restricting passenger cars, particularly diesel cars as well as HDVs. Many of the studies, however, have used simple statistical methods that have not taken sufficient account of the confounding factors that affect urban air quality. Studies that have used more sophisticated statistical analyses to remove the confounding factors, particularly the effects of meteorology, suggest that the German LEZs may have resulted in a small, possibly a few percent, reduction in long term average PM_{10} and NO_2 concentrations.

On the other hand there is some, albeit limited, evidence that LEZs may result in larger reductions in the concentration of carbonaceous particles, which may be beneficial for public health (WHO, 2012). This must imply that PM_{10} mass concentrations have also diminished by a small amount.

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TABLE LEGENDS

Table 1: Summary of European Low Emission Zones

Table 2: Evolution of the Emissions Criteria for the London LEZ

Table 3: Estimated Impact of London LEZ in 2005 (TRL, 2000)

Table 4: Predicted Air Quality Benefits of the Recommended London LEZ in 2007 and 2010 (Watkiss et al., 2003)

Table 1: Summary of European Low Emission Zones

Country	Number of LEZs	Applicable vehicles	National Framework/ legislation
Austria	3	Heavy goods vehicles (HGVs)	Yes
Czech Republic	1	HGVs	No
Denmark	6	HDVs	Yes
Finland	1	Buses and refuse trucks	No
France	1	HGVs	No
Germany	~70	All vehicles except motorcycles	Yes
Greece	1	All vehicles in inner LEZ, vehicles > 2.2 tonnes outer LEZ.	No
Italy	~92**	Various	No
Netherlands	13	HGVs	Yes
Portugal	1	Cars & HGVs	No
Sweden	8	All vehicles > 3.5 t	Yes
UK	3	HDVs and in London also large commercial LDVs.	No
EU	~200	-	No

Notes:
***The Lombardi Regional LEZ has been counted as one.
Table only includes those in existence in 2014. LEZs are planned for Belgium and Czech Republic.
Source: (http://urbanaccessregulations.eu) / Sadler Consultants Ltd, 2014b

Table 2: Evolution of the Emissions Criteria for the London LEZ

Phase	Date Introduced	Vehicles Restricted	Gross vehicle weight (GVW) (tonnes)	Minimum Emission standard*
1	4 Feb 2008	Heavy goods vehicles (HGVs)	> 12 t	Euro III for PM
2	7 July 2008	HGVs	> 3.5 t	
3	3 Jan 2012	Large vans 4x4 light utility vehicles Motorised horseboxes Pickups	1.205 (unladen) -3.5 t (GWV)	Euro III
		Ambulances Motor caravans	2.5 - 3.5 t	
		Minibuses (>8 passengers)	≤5 t	
4	3 Jan 2012	HGVs	> 3.5 t	Euro III
		Buses, coaches	>5 t	
5	Dec 2015	Buses operated by Transport for London		Euro IV
6	Planned for 2020	All vehicles. This ultra-low emissions zone is currently under development, and may apply just within the 22 km^2 of the London Congestion Charging Zone in Central London, and for restricted hours.	All vehicles	Euro 6/VI (?)

Notes:

* Or fitted with a diesel particle filter with a Reduced Pollution Certificate. Euro III and Euro IV standards were mandated for all vehicles first registered after October 2001 and 2005 respectively.

752 **Table 3:** Estimated Impact of London LEZ in 2005 (TRL, 2000)

Location	**Estimated change in emissions compared to a 'do nothing' scenario**		**Average Background Concentrations ($\mu g\ m^{-3}$)**		**Average Urban Centre Concentrations ($\mu g\ m^{-3}$)**
	PM_{10}	**NO_x**	**PM_{10}**	**NO_2**	**NO_2**
Central London	-55%	-20%	20.7	34.2	35.7
Inner London	-48%	-19%	19.5	31.8	38.5
Outer London	-46%	-18%	19.2	27.3	30.3
All London	-47%	-18%	n/a	n/a	n/a

Notes:
The original paper used ppb for NO_2, the conversion to $\mu g\ m^{-3}$ used a factor of 1.88 to be consistent with other data in this report.

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Table 4: Predicted Air Quality Benefits of the Recommended London LEZ in 2007 and 2010 (Watkiss et al., 2003)

Scenario:			
	Year	**NO_x**	**PM_{10}**
Reduction in emissions (relative to baseline)	2007	1.5%	9.0%
	2010 (A)	2.7%	19%
	2010 (B)	3.8%	23%
	Year	**NO_2**	**PM_{10}**
Reduction in area exceeding air quality targets (relative to baseline)	2007	4.7%	0%*
	2010 (A)	12.0%	32.6%**
	2010 (B)	18.9%	42.9%**

Notes:
*London should meet the relevant air quality objectives for PM_{10} in an average meteorological year.
** Exceedence of the provisional annual mean PM_{10} objective of 23 µg m^{-3} (40 µg m^{-3}applicable in 2007). This objective was removed in the 2007 Air Quality Strategy.
2010 (A) HDVs
2010 (B) HDVs, vans and taxis

Highlights

- Most studies of LEZs have not taken confounding factors into account adequately
- German LEZs may have reduced PM_{10} and NO_2 concentrations by a few percent
- Elsewhere no clear effects on PM_{10} and NO_2 observed
- Carbonaceous particle concentrations may be reduced significantly

Supplementary Information

Table S1: Summary of the Air Quality Benefits of LEZs Identified From Monitoring Data

City	Reduction in Long Term Concentrations Due to LEZ (%)								Notes	Reference
	PM_{10}	$PM_{2.5}$	PM_1	BC	EC	Abs.	NOx	NO_2		
Berlin, Manheim, Stuttgart, Tubingen, Ludwigsburg	No effect								Comparison of cities with and without LEZs	Nierderemaier, 2009, cited in Cyrys et al., 2014
17 German cities with LEZs								Up to 4%	Matched quadruplets for before and after LEZ and within LEZ and at reference stations. LEZ Stage1.	Morfeld et al., 2014
Berlin, Cologne	5-7%								Comparison of annual average concentrations	Bruckmann and Lutz, 2010, cited in Cyrys et al., 2014
Berlin	3%				14-16%				Comparison of BS concentrations within and outside LEZ. Adjusted for the changes in traffic intensity. 2008 (with LEZ) compared to 2007	Lutz, 2009
					42% (traffic contribution)			7-10%	Comparison between 2007 (no LEZ) and 2012	Lutz, 2013
Bremen	6%							6%	No details provided	Reported in Sadler, 2011

City	Reduction in Long Term Concentrations Due to LEZ (%)								Notes	Reference
	PM_{10}	$PM_{2.5}$	PM_1	BC	EC	Abs.	NOx	NO_2		
Cologne	7%							1.5%	Early estimate from monitoring data. PM_{10} affected by construction works	Reported in Sadler, 2011
Hanover	1-2%							5%	No details provided	Reported in Sadler, 2011
Leipzig	No effect (6-15% in summer)				6-14% (14-29% in summer)				Comparison of annual/summer average concentrations, adjusted wrt reference station	Löschau et al., 2013, cited in Cyrys et al., 2014
Ruhr Area	4%							1.2%	Comparison of average concentrations in and out of LEZ	Reported in Sadler, 2011
Munich	5-12%								Ban in through HDV traffic introduced 8 months before LEZ. Analysis based on 4 months monitoring data, adjusted wrt reference station	Cyrys et al., 2009, cited in Cyrys et al., 2014
	No effect								Comparison before and after LEZ, adjustment using reference station data	Morfeld et al., 2013, cited in Cyrys et al., 2014

City	Reduction in Long Term Concentrations Due to LEZ (%)								Notes	Reference
	PM_{10}	$PM_{2.5}$	PM_1	BC	EC	Abs.	NOx	NO_2		
	13% (19.6% in summer; 6.8% in winter)								Data for traffic site; 4.5% reduction in annual mean at urban background. Analysis took account of multiple factors using semi-parametric regression model. HDV ban as well as LEZ	Fensterer et al., 2014
					55% (traffic contribution)				Positive matrix factorization of $PM_{2.5}$ samples collected before and after LEZ.	Qadir et al., 2013
Milan	No effect	No effect	No effect						Very short term data. Ratio of BC to PM_{10} lower in LEZ than outside.	Invernizzi et al., 2011
Amsterdam, The Hague, Den Bosch, Tilburg, Utrecht	No effect	No effect				No effect	No effect	No effect	Comparison before and after LEZ (and in some cases other traffic measures), four suburban stations used as reference stations.	Boogaard et al., 2012
Amsterdam	No effect				12.9% (limited data)	7.7% (limited	No effect	No effect	Linear regression. Traffic	Panteliadis et al., 2014

City	Reduction in Long Term Concentrations Due to LEZ (%)								Notes	Reference
	PM_{10}	$PM_{2.5}$	PM_1	BC	EC	Abs.	NOx	NO_2		
						data)			contribution estimated by subtracting data from urban background monitoring site in LEZ.	
Copenhagen		5%					No effect		Comparison of data from traffic site before and after LEZ.	Jensen et al., 2011
London	No effect	5-11% (per year) (traffic contribution)		15-17% (per year) (Traffic contribution)			3-7% (Traffic contribution)	No effect	Detailed filtering of data to remove confounding factors. Data from sites most likely to be affected by LEZ	Barrett, 2014
	1-2%						No effect		Simple comparison of data from sites in and outside LEZ.	Ellison et al., 2013

Notes: Sadler (2011) provides a review of the efficacy of LEZs, and is more optimistic than Cyrys et al (2014). Little detail of the methodology used to identify the LEZ effect is given. In this Table data from Sadler (2011) has only been included for those LEZs that there is no other source is readily available. Data is derived from measurements not modelling.

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